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INJURY MECHANISMS AND TOLERANCE OF THE HUMAN ANKLE JOINT

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Paper was presented at the 20th Annual Workshop on Human Subjects for Biomechanical Research. This paper has not been screened for accuracy nor refereed by any body of scientific peers and should not be referenced in the open literature.

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CALSPAN/UNIVERSITY OF BUFFALO RESEARCH CENTER (CUBRC)

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Injury Mechanisms and Tolerance of the Human Ankle Joint

This program was performed for the Center for Disease Control under grant application number R49CCR 203615-01. The testing was performed by the Calspan/University of Buffalo Research Center (CUBRC) located in Buffalo, New York. The authors include David Roberts and Bruce Donnelly of Calspan, and Dr. Charles Severin and Dr. John Medige of the University of Buffalo.

After reviewing of the existing literature on foot-ankle-leg injuries for front seat automobile occupants involved in frontal impacts, it was found that there is little information available on injury mechanisms.

An impact scenario, based on a review of the limited literature, is shown in Figure 1. A driver or passenger is seated in the front seat of an automobile. The occupants' feet are placed on the floorboard and/or pedals. During a frontal impact the occupant continues to move forward and knee contact with the instrument panel occurs. At this point the leg has become "trapped" between the instrument panel and floorboard. Finally, intrusion of the floorboard into the occupant compartment occurs and the leg becomes axially loaded.

Five hypotheses, listed in Figure 2, were proposed for this program based primarily on an earlier study entitled <u>Injury Mechanism of Axial Load to the Leg</u>. This earlier study was performed for the National Highway Transportation Safety Administration (NHTSA) and involved static axial loading of the ankle joint/foot complex.

LIKELY EXPOSURE SCENARIO

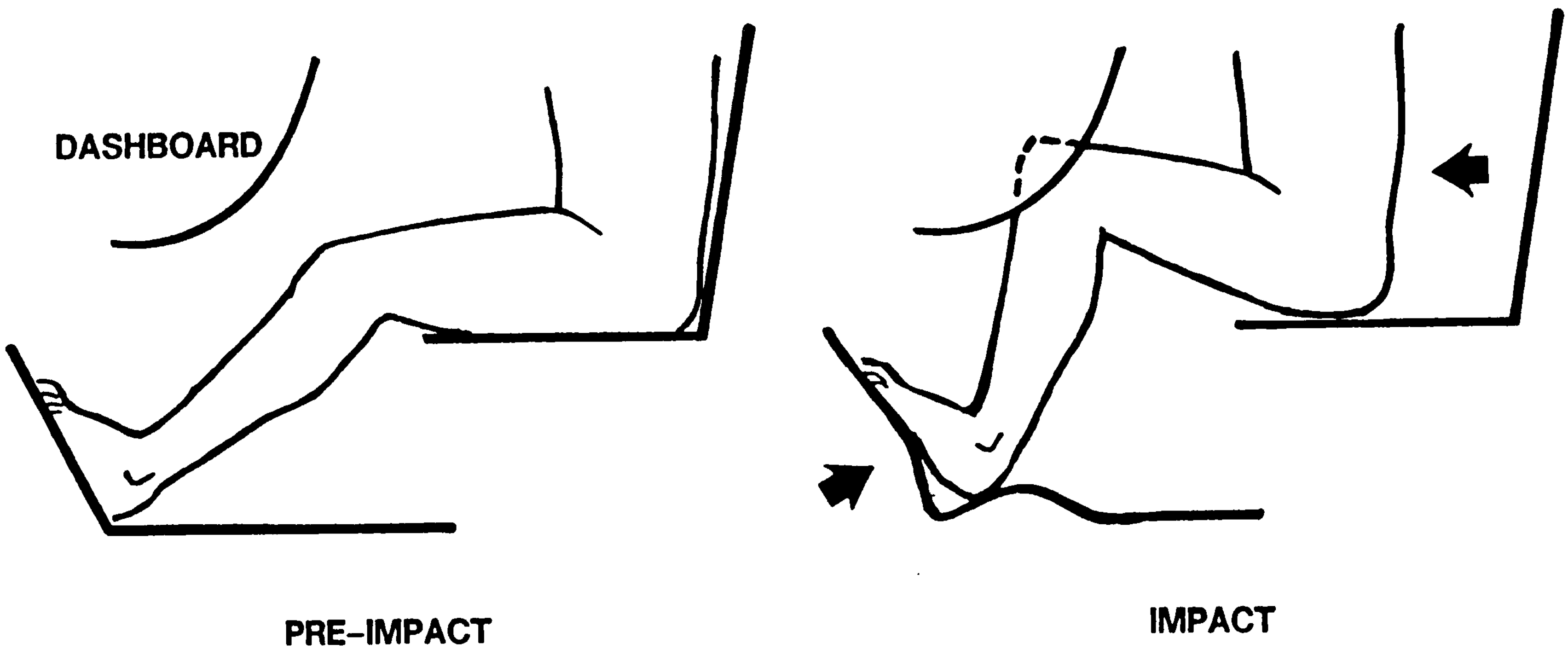


FIGURE 1

HYPOTHESES

- PRIMARY INJURIES ARE A RESULT OF EVERSION OF THE ANKLE JOINT.
- EVERSION CAUSES COMPRESSION INJURIES ON THE LATERAL SIDE AND TENSILE INJURIES ON THE MEDIAL SIDE OF THE FOOT.
- STIFFENING EFFECT OCCURS IN DYNAMIC VERSUS STATIC.
- IMPACT SCENARIO (DESCRIBED EARLIER) IS REALISTIC FOR BOTH STATIC AND DYNAMIC AXIAL LOADS.
- INJURIES IDENTIFIED ARE SIMILAR TO THOSE FOUND IN REAL WORLD.

FIGURE 2

The objectives of this test program, performed at the Calspan/University at Buffalo Research Center (CUBRC), were:

1. To measure applied static and dynamic axial loads and displacements at failure in a cadaver leg with the foot in 20° dorsiflexion.

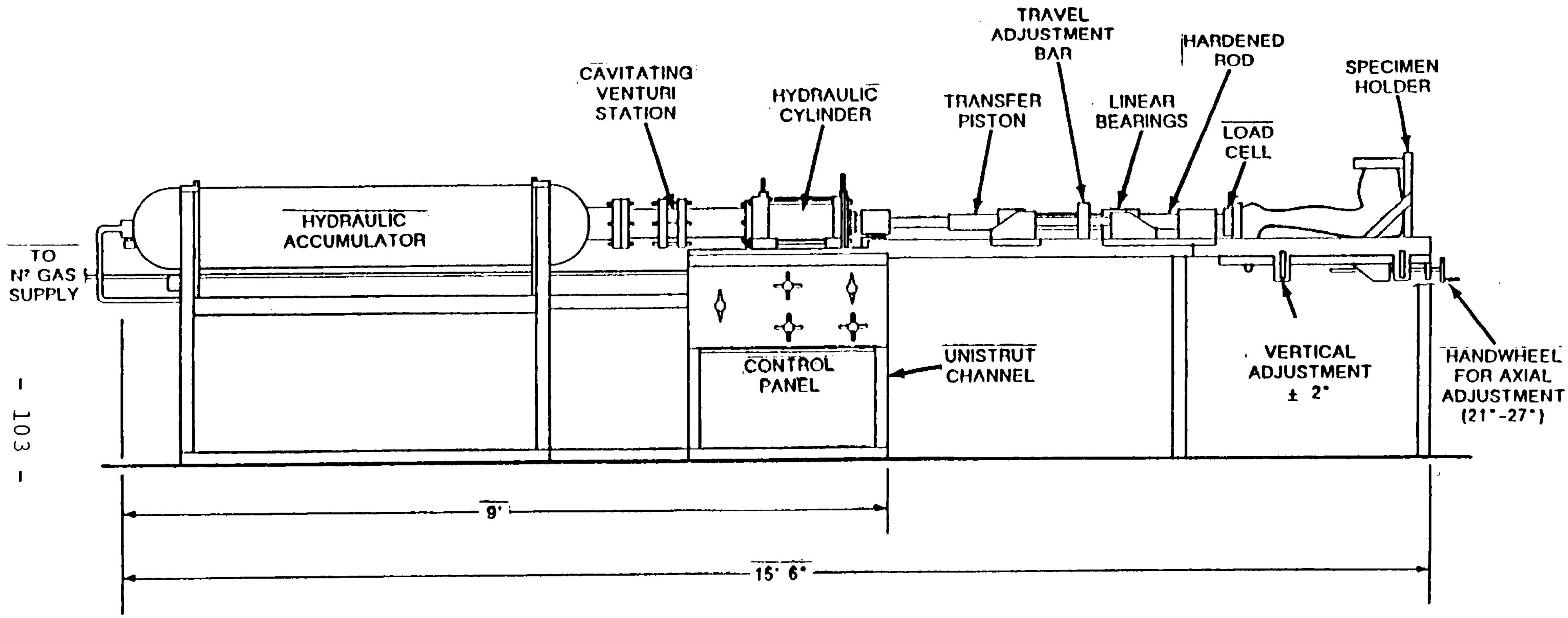
2. To identify the extent of the injuries with particular emphasis on the ankle joint.

3. To identify the injury mechanism(s) involved.

4. To quantify human ankle joint and bone tolerance to axial loading.

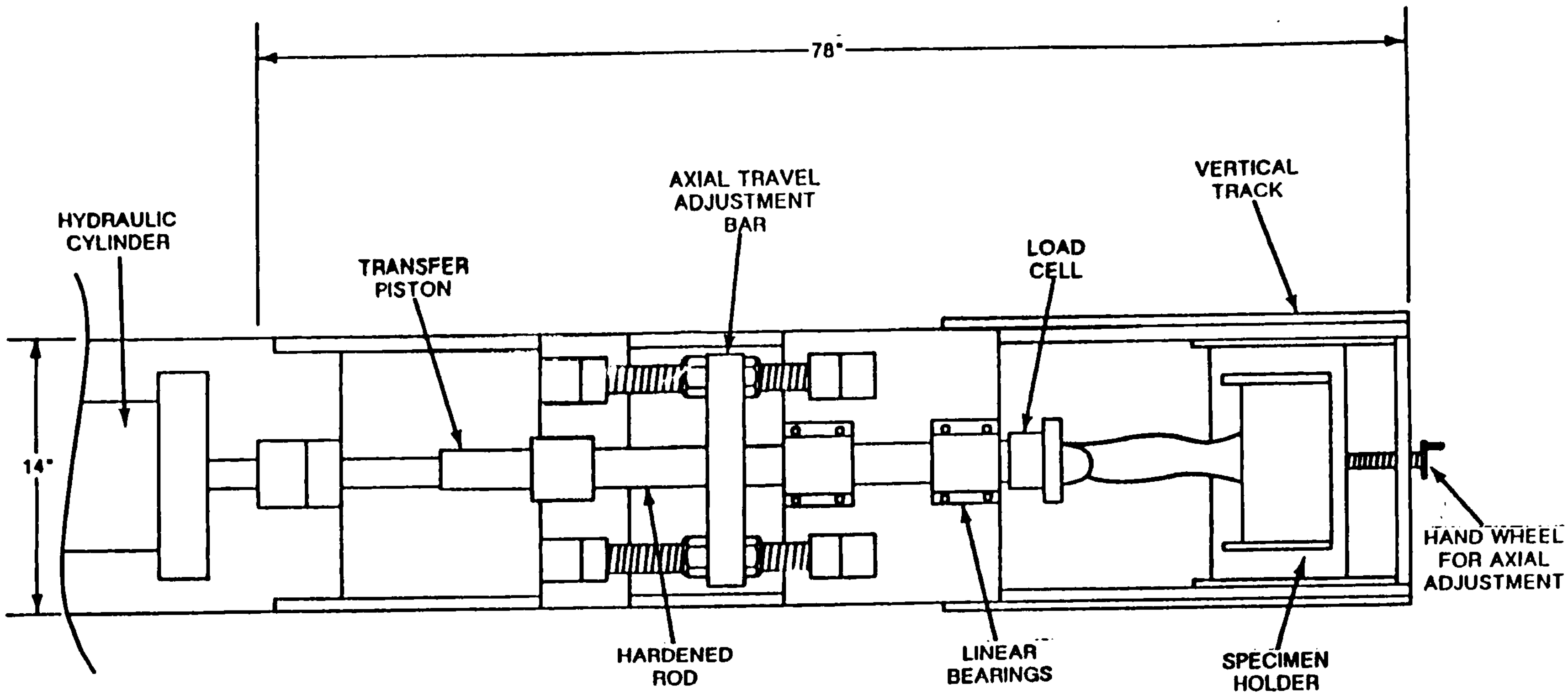
The testing was performed using a newly developed constant velocity compression device, which delivers a constant velocity over a specified displacement regardless of the resistive force. This equipment was used for the dynamic testing while a hydraulic ram was used for the static testing. A total of 12 subjects were tested (4 female and 8 male) with each lower limb tested in either a static or dynamic mode for a total of 24 tests. Each specimen was placed in the test fixture with the foot placed in a 20° dorsiflexion. The static displacement at failure was used to identify the total stroke allowed in the dynamic test. A five-axis load cell was used to measure three forces and two moments and an Endevco accelerometer was used to measure acceleration. Two high-speed cameras and videos were used to record the tests. Data was collected on a personal computer using software developed at Calspan.

Figures 3 and 4 show the constant velocity compression device in a lateral and top view, respectively. A description of this device was given in a previous paper



CONSTANT VELOCITY COMPRESSION DEVICE
LATERAL VIEW

FIGURE 3



CONSTANT VELOCITY COMPRESSION DEVICE
TOP VIEW

FIGURE 4

entitled Design and Operation of a Constant Velocity Compression Device for Biomechanical Research.

Figure 5 is a schematic of the test apparatus with a left leg in place for axial loading. The foot was placed at a 20° dorsiflexion and was retained at this angle throughout the test by means of the 20° loading plate. For all tests the centerline of the compression device was aligned with the foot in a sagittal plane and the tibia was parallel to the shaft of the impact. The knee/thigh was held captive and not allowed to move throughout the test.

Figure 6 is a top view schematic of the posterior portion of a right leg showing the injury mechanism during static axial loading. In all 12 static tests performed there was an eversion of the foot during loading. This created compressive forces on the lateral side of the foot and tensile forces on the medial side of the foot. The eversion increased with increasing load until a failure of the ankle occurred. Failure was established when the real time force-displacement curve showed a 50% drop in the peak force level. At this point the test was terminated.

Figure 7 presents a list of injured tissues for the static and dynamic tests for each specimen. The figure is divided into hard and soft tissue injuries. The injuries for the static tests are generally tensile in nature on the medial side and compressive on the lateral side for both the soft and hard tissues. The dynamic tests caused injuries of a compressive nature with most fractures due to crushing. The soft tissue injuries in the dynamic case were primarily due to lacerations caused by the underlying hard tissue fractures.

Figures 8 and 9 show the axial load versus displacement for the static and dynamic tests, respectively. Both figures show that as the peak axial load increased, the displacement also increased. The dynamic peak axial loads are approximately 50%

SCHEMATIC OF LEFT LEG IN TEST APPARATUS FOOT PLACED AT 20° DORSI FLEXION

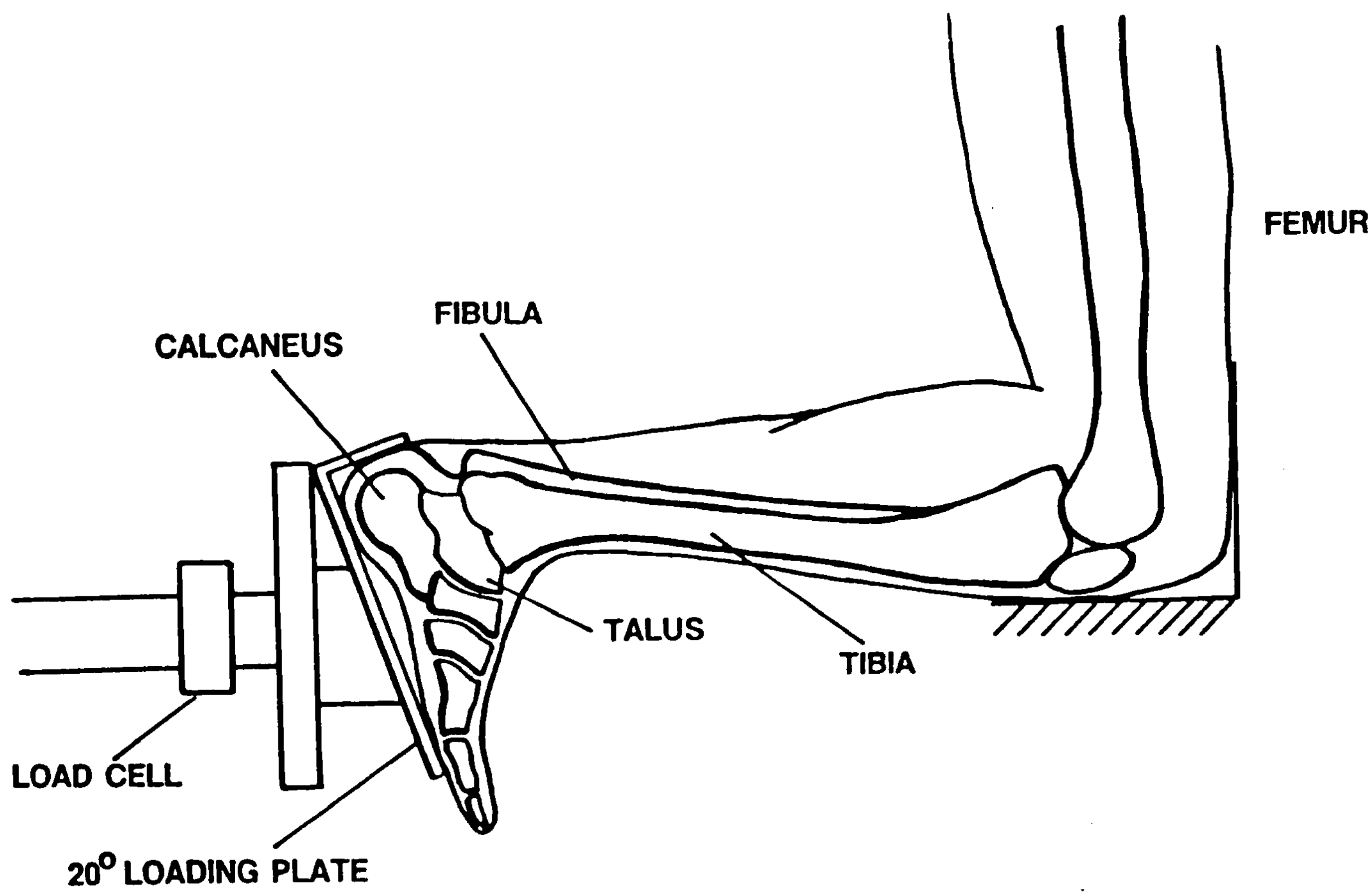


FIGURE 5

SCHEMATIC OF INJURY MECHANISM DURING AXIAL LOAD

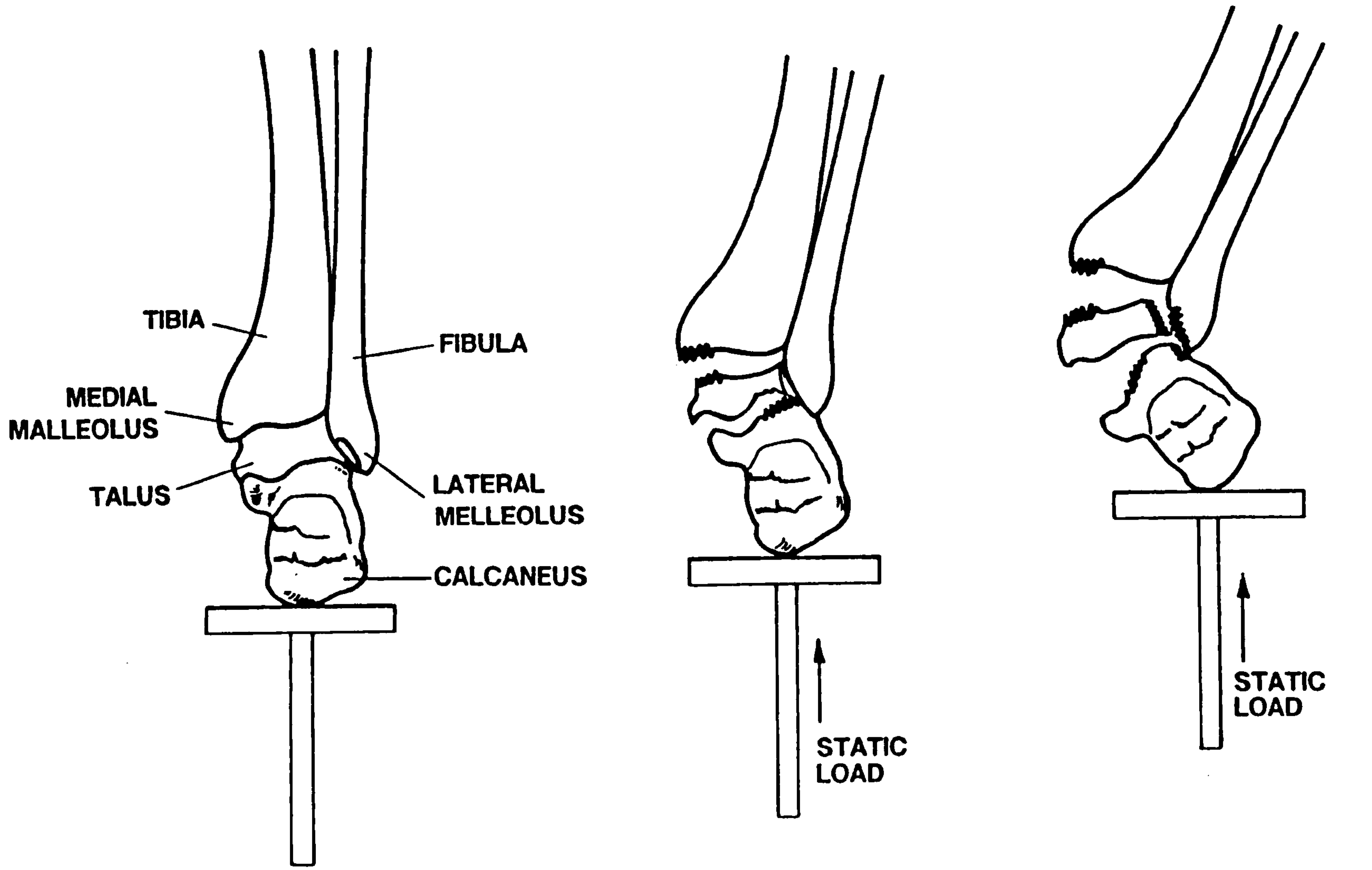


FIGURE 6

SUMMARY OF INJURIES

	STATIC												DYNAMIC											
INJURY	1	2	3	4	5	6	7	8	9	10	11	12	1	2	3	4	5	6	7	8	9	10	11	12
HARD TISSUE																								
NAVICULAR															●									
TALUS			●											●	●	●					●			
CALCANEOUS			●					●				●			●		●	●		●			●	
ARTICULAR SURFACE TIBIA		●	●		●	●													●					
ARTICULAR SURFACE FIBULA			●											●										
ARTICULAR SURFACE TALUS		●	●	●	●						●	●		●		●	●	●	●		●		●	●
MEDIAL MALLELOLUS	●	●	●	●	●		●		●		●					●								
LATERAL MALLELOLUS			●												●									
TIBIA		●		●			●		●	●		●				●			●		●			
FIBULA	●			●					●					●	●	●			●		●			
SOFT TISSUE																								
FLEXOR HALLICIS																							●	
FLEXOR DIGITORUM LONGUS					●																			
INFERIOR TRANSVERSE	●																							
PLANTAR CALCANIONANICULAR								●																
TIBIALIS POSTERIOR							●																	
DELTOID		●	●														●							
INTEROSSEOUS TALOCALCANEOUS																				●				
RETINACULA														●										
INTEROSSEOUS MEMBRANE																				●				
JOINT CAPSULE							●														●			●
PERONEOUS LONGUS								●																
PERONEOUS BREVIS								●																
SKIN											●				●				●	●				

FIGURE 7

AXIAL LOAD VERSUS DISPLACEMENT
STATIC

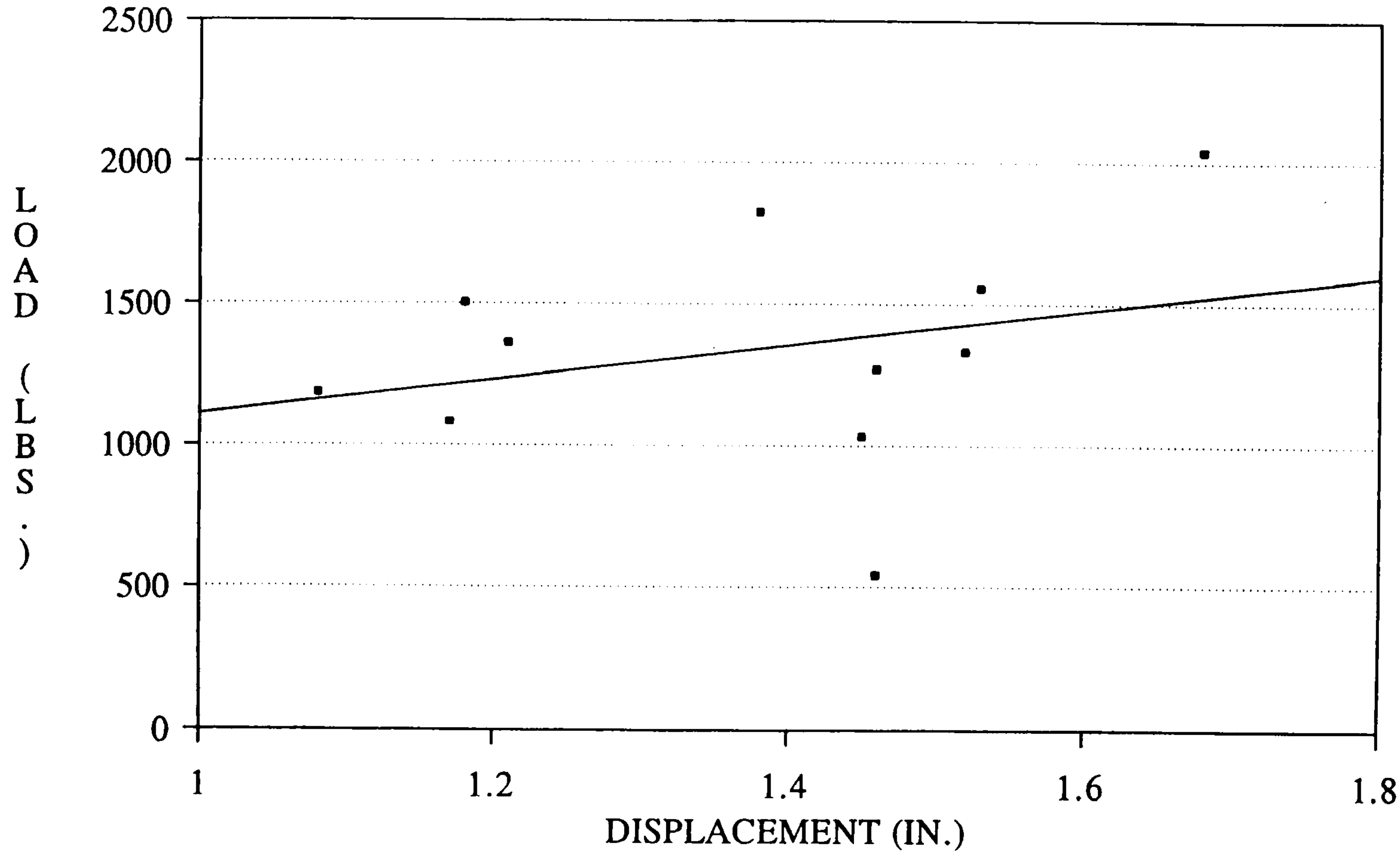


FIGURE 8

AXIAL LOAD VERSUS DISPLACEMENT
DYNAMIC

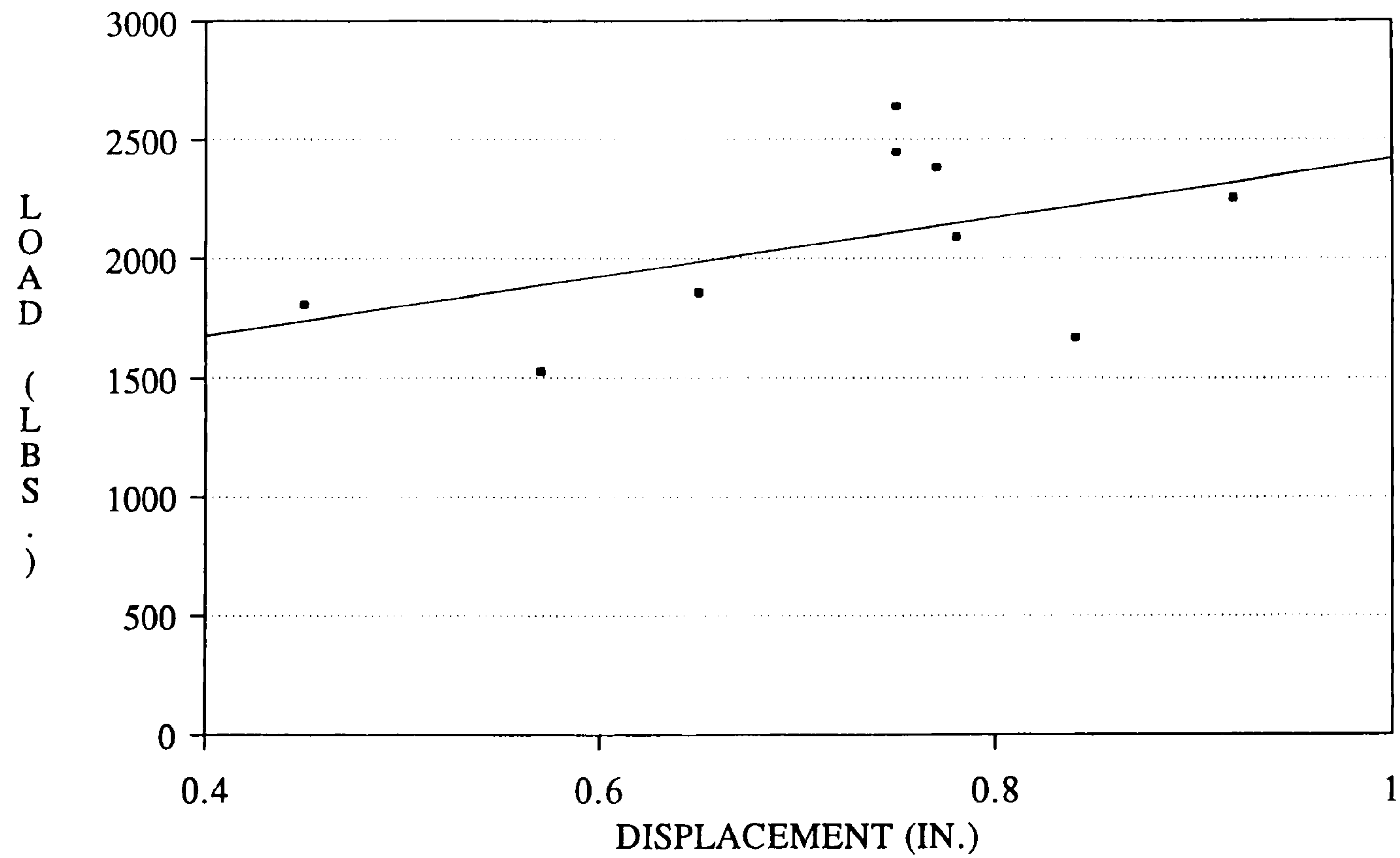


FIGURE 9

more than the static peak loads, while the maximum displacements in the dynamic cases are approximately half of the maximum displacements observed in the static cases. These observations are also shown in Figures 10 and 11. Figure 10 depicts the maximum axial load for each subject from static and dynamic loading. Note that the dynamic loads are approximately 50% more than the static loads. Figure 11 depicts the maximum displacement at failure for each subject from static and dynamic tests. Note that the dynamic tests show displacements of approximately half of those seen in the static tests.

The preliminary results include:

(1) Peak axial loads are approximately 50% higher in the dynamic case versus the static case.

(2) Peak axial displacements are approximately 50% lower in the dynamic case versus the static case.

(3) The dynamic test shows little tendency for eversion.

(4) Injuries in the static tests are compressive on the lateral side of the ankle and tensile on the medial side of the ankle.

(5) Injuries in the dynamic tests are compressive.

(6) Maximum dynamic displacement at failure averages approximately 0.75 inches.

Additional analyses for this test program will include:

(1) Torsion testing of the tibia to relate bone strength to injury.

(2) Abbreviated Injury Scaling (AIS) of the injuries.

MAXIMUM AXIAL LOAD

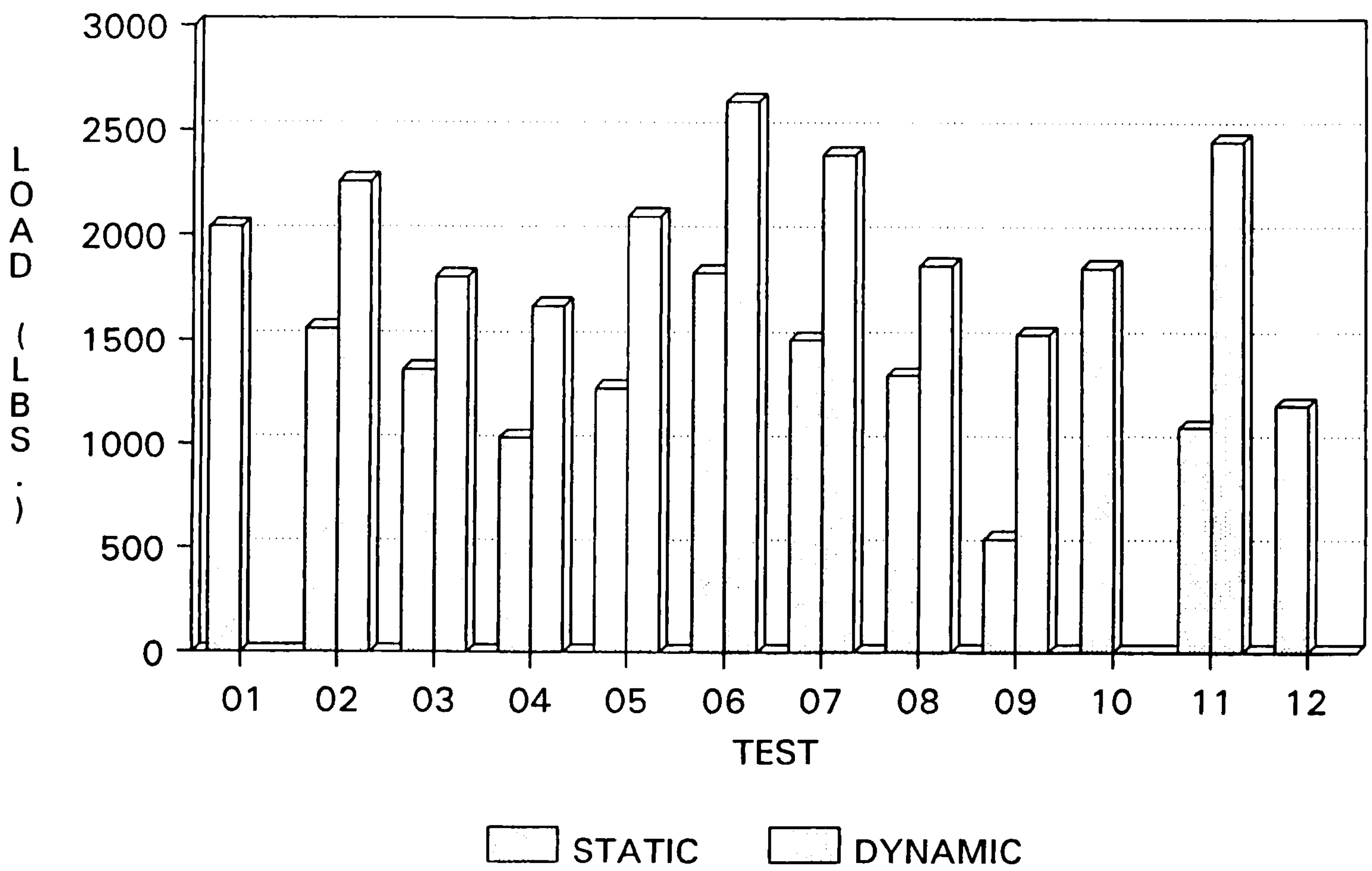


FIGURE 10

MAXIMUM DISPLACEMENT AT FAILURE

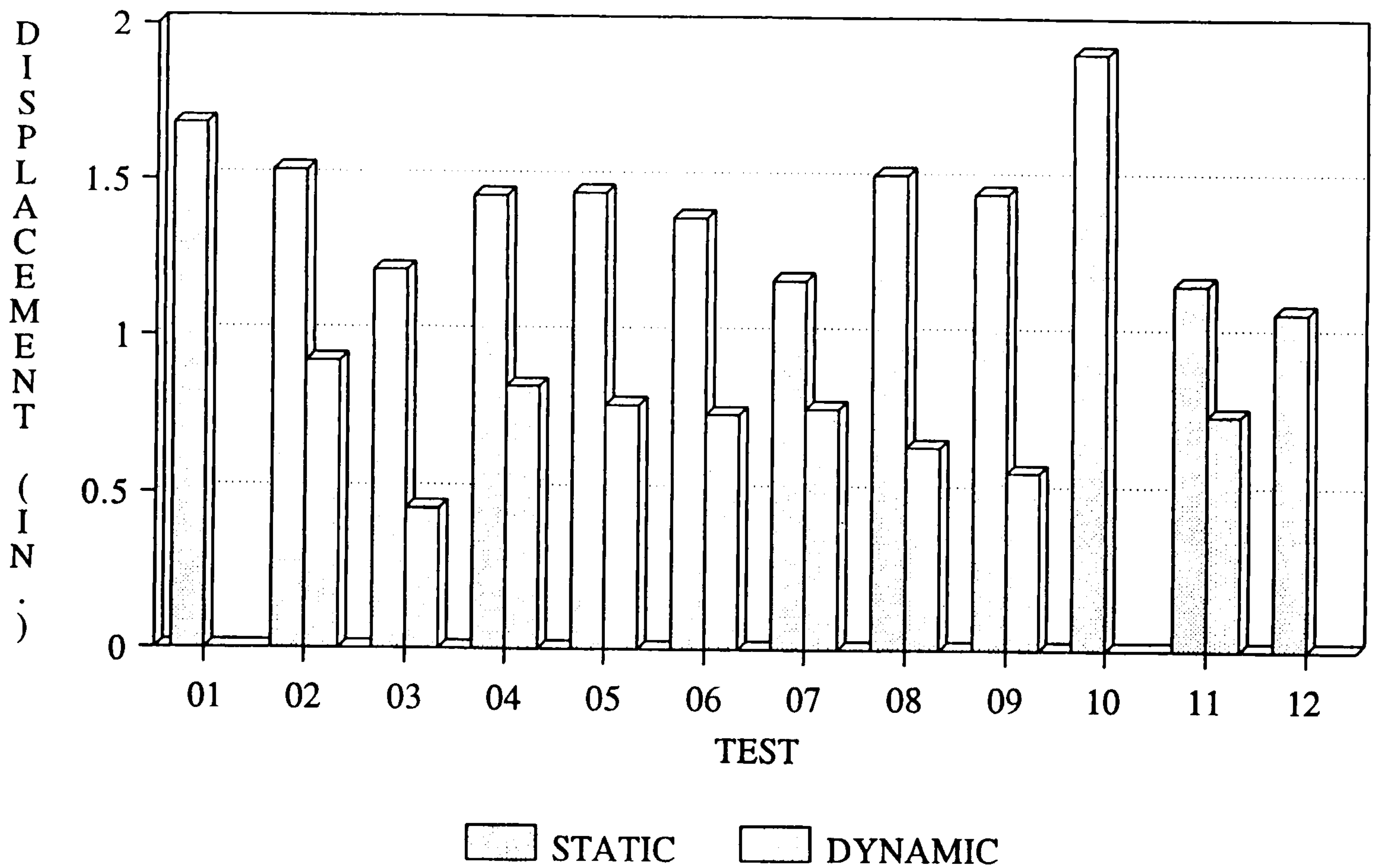


FIGURE 11

(3) Load-moment data analyses.

(4) Subject parameter analyses.

(5) Disability index of injuries.

Future work may include:

(1) 0 degree flexion tests.

(2) 20 degree plantar flexion tests.

(3) Load plate angle changes.

(4) Verification of testing using Hybrid III legs.

The authors wish to acknowledge Mr. Thomas Bartenfeld and Mr. Theodore Jones from the CDC for their interest and encouragement in this program.

DISCUSSION

PAPER: **Injury Mechanisms and Tolerance of the Human Ankle Joint**

PRESENTER: D. Roberts

FELLOW AUTHORS: Bruce Donnelly, C. Severin, J. Medige

QUESTION: Dr. Levine, Wayne State University

First of all, I think some of what you've done was probably done about forty years ago by Lang Hanson and they did look at ankle injuries and mechanisms. I think what you're describing as a frac phasing did crush the fibula is probably a bending. Because as you hurt the foot you evulse the medium melelius, you may tear the enasus ligament. If you keep going, you'll bend the fibula if you don't get a crush on it. You'll probably transfer its fraction, it may rupture. I can't tell you. We don't talk about fibula crushes in the lateral melelius, with emergent injuries like you were showing.

A: Well, actually looking at the bone, looking right below the fibula, that's shown some crushing and some slight crushing of the articular surface. You're right though, the fibula is more bending.

Q: Craig Morgan, Denton, Inc.

Were you able to subtract out the dynamic loading into the load cell from the mass of the fixture?

A: John would be able to answer that better. He says "yes, we did."

Q: Rolf Eppinger, NHTSA

Ultimately when we want a criteria, we want to have a criteria that says if I meet this criteria we do not have failure and if you have a dynamic event (in) which you have failure and a velocity, you still would, in order to successfully go through that event, you have to bring the velocity back down to zero without injuries. So my question is, first off, have you run any dynamic tests where you had no failures so you could understand the loading and unloading phase of that and then do you have any impressions on whether it is the displacement or the peak load that is the more effective or the causal agent in the fracture?

A: All tests that we performed work dynamically where there were injuries involved. As far as what's more important, peak load or the velocity, it's hard to tell and it's to pull out of this data right now because of the fact that we're still allowing that full displacement to occur. We are getting a peak load and even though what we are calling the peak load, which may or may not be failure, occurs at around 3/4 of an inch, we are still allowing that full stroke which we saw in the dynamic phase which may be 1-1/2 inches or so. So it's hard to tell whether those injuries occurred later on or at the peak load.

Q: Do you have any plans to pursue that a little further to see what would be a safe condition rather than going off to all the other geometric variations first?

A: That's a good point. Yes.

Q: Richard Morgan, NHTSA

If I may ask a question from the chair...Dave, may I ask you and may I also ask Dr. Levine, what is the difference in the test setup that we have here at Calspan and the test setup that Wayne State University has been using for their ankle tests? Here comes Dr. Levine.

A: I don't know the car setup. I've only looked at the ankles after the injuries trying to find cause of injuries, but I believe ours allows more motion than this one. One thing obviously for sure is that we have constant velocity. I mean that's something unique to our device.